Eruption and Emplacement Mechanisms and Paleoenvironment of Phreatomagmatic Tephra at Koko Crater Tuff Cone, O'ahu, Hawaii

by

Elizabeth Louise Simoneau

B.S., University of Central Missouri, 2006

Submitted to the Graduate Faculty of the

Kenneth P. Dietrich School of Arts and Sciences

in partial fulfillment of the requirements for

the degree of Master of Science

University of Pittsburgh

2011

UNIVERSITY OF PITTSBURGH

DIETRICH SCHOOL OF ARTS AND SCIENCES

This thesis was presented

by

Elizabeth Louise Simoneau

It was defended on

July 25, 2011

and approved by

Dr. Michael Ramsey, PhD, Professor

Dr. William Harbert, PhD, Professor

Dr. Ian Skilling, PhD, Thesis Director

ERUPTION AND EMPLACEMENT MECHANISMS AND PALEOENVIRONMENT OF PHREATOMAGMATIC TEPHRA AT KOKO CRATER TUFF CONE, O'AHU, HAWAII

Elizabeth Louise Simoneau, M.S.

University of Pittsburgh, 2011

The emplacement processes of proximal tuff cone deposits are often difficult to distinguish. This thesis focuses on the steep outer flank and surrounding apron deposits of Koko Crater, O'ahu, Hawaii. Four sections were logged in detail and interpreted. The steep outer slope deposits are dominated by slumped pyroclastic fallout deposits, some of which may be directly eruption-fed, and minor pyroclastic density current (PDC) deposits, that are rarely slumped. The lack of slumping of the PDC deposits is interpreted as due to their lower eruption volumes, lower depositional rates, lower water content, and longer transport distances, all of which favor more stable slopes. Slumping is also less common on previously slumped substrate, as slumps typically generate a lower gradient than the primary deposits. The occurrence of PDC deposits overlying fallout deposits, may suggest that the PDC deposits were generated by column collapse (partial, sustained or complete). The flanking apron deposits, i.e. those around the base of the steep outer slopes, are dominated by pyroclastic density current, with minor fallout deposits. Slumping is rare in the flanking apron deposits, probably because of the lower substrate gradients. The increasing abundance of PDC deposits with distance from the vent is most likely due to the longer transport distance compared to the ballistic fallout.

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

1.1 RATIONALE/SIGNIFICANCE

A detailed understanding of the emplacement mechanisms of tuff cones and rings is important because after Strombolian cones, tuff cones are the most abundant type of volcanic edifice on Earth (Sigurdsson et al., 2000). Tuff cones and rings are generated by magma-water interaction, and hence their deposits are also important as they represent the most common products of this type of interaction that are available for study. Tuff rings are typically less than 50m high and are characterized by small depth to width ratio craters at or above ground level, and they also typically have relatively low ejecta rims with beds dipping less than 25º. Tuff cones have a higher profile than rings and steeper proximal external slopes dipping more than 25º, with their crater floors generally being above the surrounding land surface. Because tuff cones in particular have such steep slopes, that are typically wet and unstable during eruptions, they are often dominated by transport and depositional processes that typify any type of steep slopes of cohesive granular materials, including fine-grained mine waste tips. Transport processes associated with such settings include grain flows, mass flows, slumps, slides and creep, associated with rill and gully development.

Controls on the generation of tuff cones versus tuff rings are poorly understood, but have been related to the hydrological conditions, specifically the recharge rates of water in the mixing zone with the magma. Tuff cones are often interpreted as having resulted from eruption in open water with a repeatedly and rapidly flooded mixing zone, whereas tuff rings are interpreted as edifices generated by interaction with more slowly recharging groundwater.

This thesis focuses on the interpretation of the emplacement (transport and deposition) mechanisms of the products of the steep subaerial, proximal outer flanks and flanking apron of a tuff cone (Koko Crater, Hawaii). The primary (i.e. not moved since initial emplacement) products of tuff cones typically include those derived from pyroclastic fallout and density currents of various concentrations, often deposited simultaneously during the same "eruptive event". Tuff cones also very commonly preserve a wide variety of "resedimented" and "reworked" deposits. Resedimented deposits are defined as those that have been remobilized after primary deposition, but before cementation, and "reworked" implies mobilization and fragmentation after cementation (McPhie et al., 1993). Resedimented and reworked deposits can be grouped together as "secondary" deposits. There is also a category of deposits often termed "eruption-fed". This term is most commonly restricted to subaerial and subaqueously emplaced flow deposits that are interpreted to have been fed directly from pyroclastic fallout, and as such may be regarded as falling somewhere between primary and resedimented.

Because primary, secondary and "eruption-fed" proximal tuff cone eruptions can all generate poorly structured (often massive) wet, cohesive, unstable deposits on steep slopes close to the angle of repose, distinguishing the three types is very difficult or impossible. The principal purpose of this study was to describe and interpret proximal tuff cone deposits at Koko Crater and to attempt to distinguish primary, secondary and "eruption-fed" emplacement mechanisms as far as possible. The study area also included three arcuate ridge-like areas, two of which are concentric, on the flanking apron beneath Koko Crater. It was not clear if these represent earlier cone/ring rims or slide blocks off the flanks of Koko Crater. This study also aimed to interpret the origins of these structures.

Koko Crater is a basanitic tuff cone situated close to the current south-eastern shore of the Hawaiian island of O'ahu (Figure 1). It is dominated by subaerially emplaced "Surtseyan" phreatomagmatic volcaniclastic deposits. This study focuses on the best exposed and most easily accessible sections, which are located at the south-eastern edge of Koko Crater. Preliminary examination of other areas of Koko Crater suggests that these south-eastern sections are also representative of the bulk of the tephra preserved at Koko Crater. The south-eastern sections also record both primary, resedimented and reworked deposits on the steep flank and the more shallowly dipping surrounding apron closest to the current shoreline.

This study will improve our understanding of the mechanisms of emplacement of proximal basaltic phreatomagmatic deposits, and specifically that it might aid the distinction between the various primary, secondary and eruption-fed processes on the steep slopes of tuff cones.

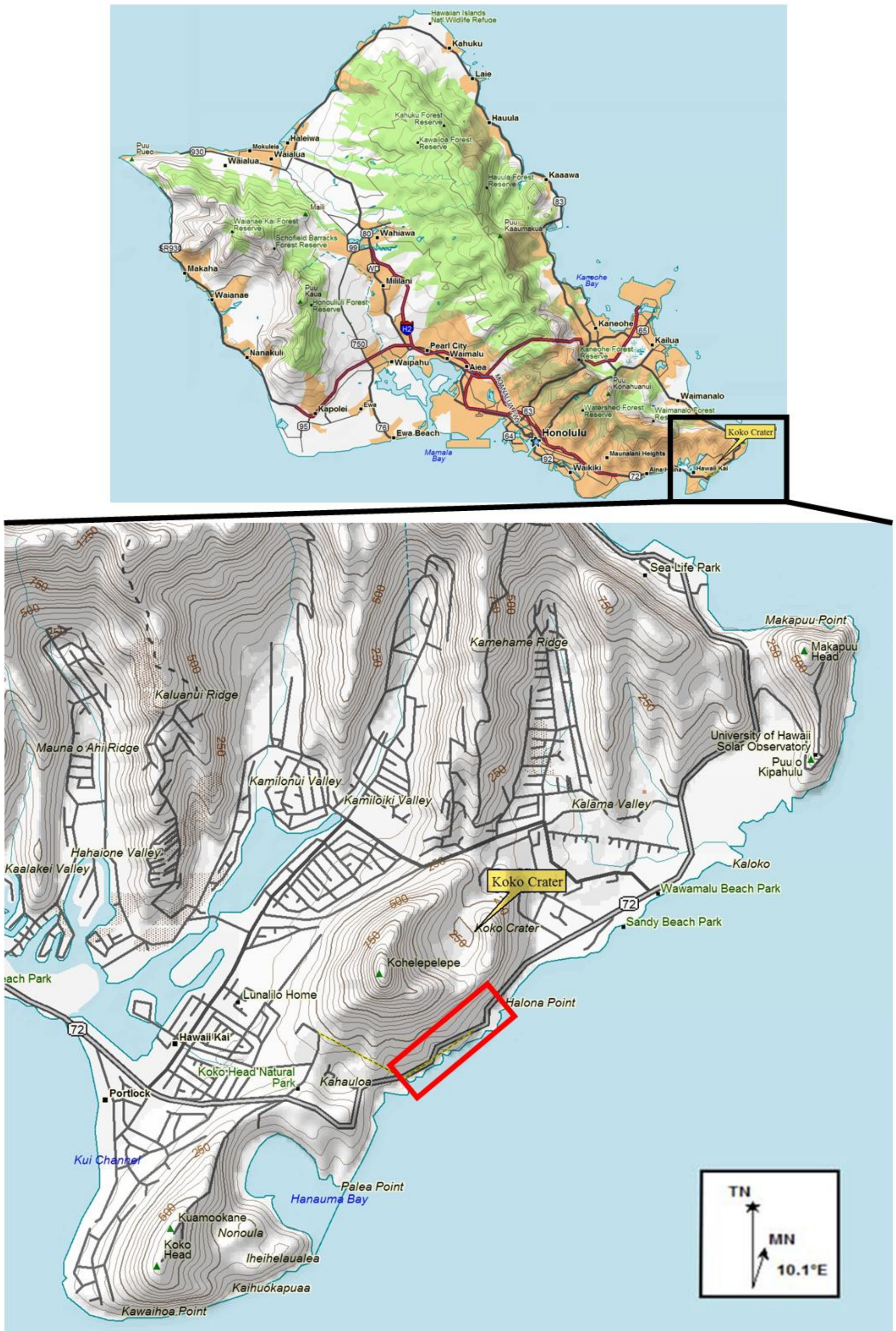

Figure 1. Topographic map of southeastern Oahu, Hawai'i. Koko Crater is marked and the area of study marked with a red box.

1.2 GEOLOGY OF OAHU

O'ahu is a 4052km^2 island located in the northwest section of the Hawaiian island chain. It was formed by two main shield volcanoes, with the deposits of the Waianae shield volcano to the west and those of the younger Koolau shield volcano to the east. The youngest of Waianae's lavas are about ~2.5 Ma old. The shield is dominantly tholeiitic with a post-shield alkalic cap and late alkali basalt flank eruptions. The earliest exposed lavas at Koolau are dated at 2.7 Ma with volcanism ending around 1.7 Ma (Self and Moberly, 1997). All of the Koolau shield lavas were tholeiitic, with no evidence of a post-shield alkalic lava flow phase, which is typical of many of the Hawaiian shield volcanoes, though it may have been removed by erosion. The pyroclastic (phreatomagmatic) deposits of the "Koko Rift" or fissure-fed series of craters in south-eastern O'ahu could be regarded as the final alkali (basanitic) phase of this shield volcano. This "rift" is part of a larger group of magmatic and phreatomagmatic onshore and offshore centres, that form the Honolulu Volcanic Series, described in the next section. Koko Crater is the most prominent crater on the Koko rift fissure system.

1.3 HONOLULU VOLCANICS

Following approximately 600 to 800 Ka of extensive erosion and isostatic subsidence of at least 350 m (1200 ft), volcanism was intermittently renewed at the southeastern portion of the Koolau Range (Macdonald and Abbott, 1970; Gramlich et al., 1971; Self and Moberly, 1997; Clague et al., 2005).

The Honolulu Volcanic Series is comprised of erupted materials from this rejuvenation stage and represents nearly all the known pyroclastic deposits on Oahu, but also includes alkalic lava flows. The composition of the lavas and pyroclastics is dominantly alkalic, and includes nepheline basalts, nepheline basanites, melilite-nephelinite basalts, and alkalic olivine basalts (Gramlich et al., 1971). The exact number of volcanic centers and eruptive events is questionable due to the production of nested craters, such as the Koko Head and Hanauma Bay tuff rings, and the masking of vents by subsequent proximal eruptions. However, the estimate is generally that the Honolulu Volcanic Series consists of as many as 40 volcanic centers (Hay and Iijima, 1968; Macdonald and Abbott, 1970; Self and Moberly, 1997; Clague et al., 2005). Ages of the eruptions, both lava flows and pyroclastics, have been relatively and absolutely established through stratigraphic analysis and C^{14} and K-Ar radiometric dating techniques (Winchell, 1947; Gramlich et al., 1971; Easton and Olson, 1976; Clague et al., 2005). Koko crater is among a group of about eight vents along the Koko rift at the southeastern end of the island, and represents the youngest members of the Honolulu Volcanic Series. The Koko Rift volcanics are described in the next section.

1.4 KOKO RIFT VOLCANICS

The basantic tuff cone of Koko Crater is situated on the “Koko Rift” in southeastern Oahu. The Koko Rift is not a rift in the strict sense, but is a term applied to a group of aligned fissure-fed cones and rings. The “rift” is a 12 km-long linear fissure that extends southwest from Manana Island to a submarine cone about 3 km past Koko Head. Renewed volcanism of the Koolau Range during the late Pleistocene resulted in eruptions along Koko Rift, which are believed to represent the youngest events on the island (Gramlich et al., 1971; Stearns, 1985; Self and Moberly, 1997; Clague et al., 2005).

Koko Crater dominates the southeastern coastline as the tallest tuff cone on O'ahu with a maximum elevation of 368 m (1208 ft). Erupted from two principal vents, the cone is horseshoe-shaped when viewed from above and asymmetric in cross-section, due to the preferential piling of ejecta on the southwestern (leeward) side by the northeasterly trade winds during eruption. Deep radial gulches incise outer slopes and have produced steep valleys and ridges. One of these gulches is clearly diverted by an earlier cone or ring rim or slide block off Koko Crater.

1.5 PREVIOUS WORK ON KOKO CRATER

Hay and Iijima (1968a, b) described and interpreted palagonitized tuffs of the Honolulu Group, briefly outlining their nature and origin, but principally focusing on their alteration mineralogy. Tuff deposits on Koko Crater consist largely of fresh and palagonitized basanite glass. They argued that a reaction of cold, percolating groundwater with sideromelane would account for vertical (to ground level) zoning from a surface layer of relatively fresh tuffs down into palagonite tuffs. Hay and Ijjima (1968a, b) suggested that palagonitization at Koko Crater likely formed during a former high stand of the sea, based on the fact that fresh tuffs underlie dense palagonite tuffs at the level of the marine terrace about 12 feet above present sea level. Hay and Iijima (1968a, b) noted that a consistent sequence of initial phillipsite, then chabazite, analcime, opal together with montmorillonite, and finally calcite occurs in vesicle and pore spaces in the tuffs.

Clague et al. (2005) dated the offshore Koko Rift extension. Lavas and volcaniclastic deposits were collected from 4 submarine cones that are part of the Honolulu Volcanics (Figure 2) and the locations of these and a few additional, but unsampled, vents demonstrate that nearly all the vents are located on or very close to the shoreline of Oahu, with the most distal vent just 12 km offshore. The samples and outcrops show that explosive volcanism at depths between about 350 and 590 m depth played a part in forming the volcanic cones. Clague et al. (2005) determined that the eruptive styles are dominantly effusive to strombolian at greater depths, but apparently include violent phreatomagmatic explosive activity at the shallower sites along the submarine southwest extension of the Koko Rift. Their new Ar- Ar ages argue that previously reported younger ages from the Koko Rift (Gramlich et al., 1971) are probably erroneously young and that the submarine vent eruptions and Diamond Head occurred between 0.5 Ma and 0.1 Ma, with the youngest ages of this range from the Koko Rift. Most previously reported ages for rocks of the Honolulu Volcanic Series, particularly those ages >0.8 Ma, are deemed unreliable according to Clague et al. (2005), either because they are inconsistent with stratigraphic sequence or because ages determined for the same vent or flow are inconsistent. The variability of results has been attributed to the presence of excess argon trapped in xenocrysts or small fragments of mantle xenoliths in the lava samples.

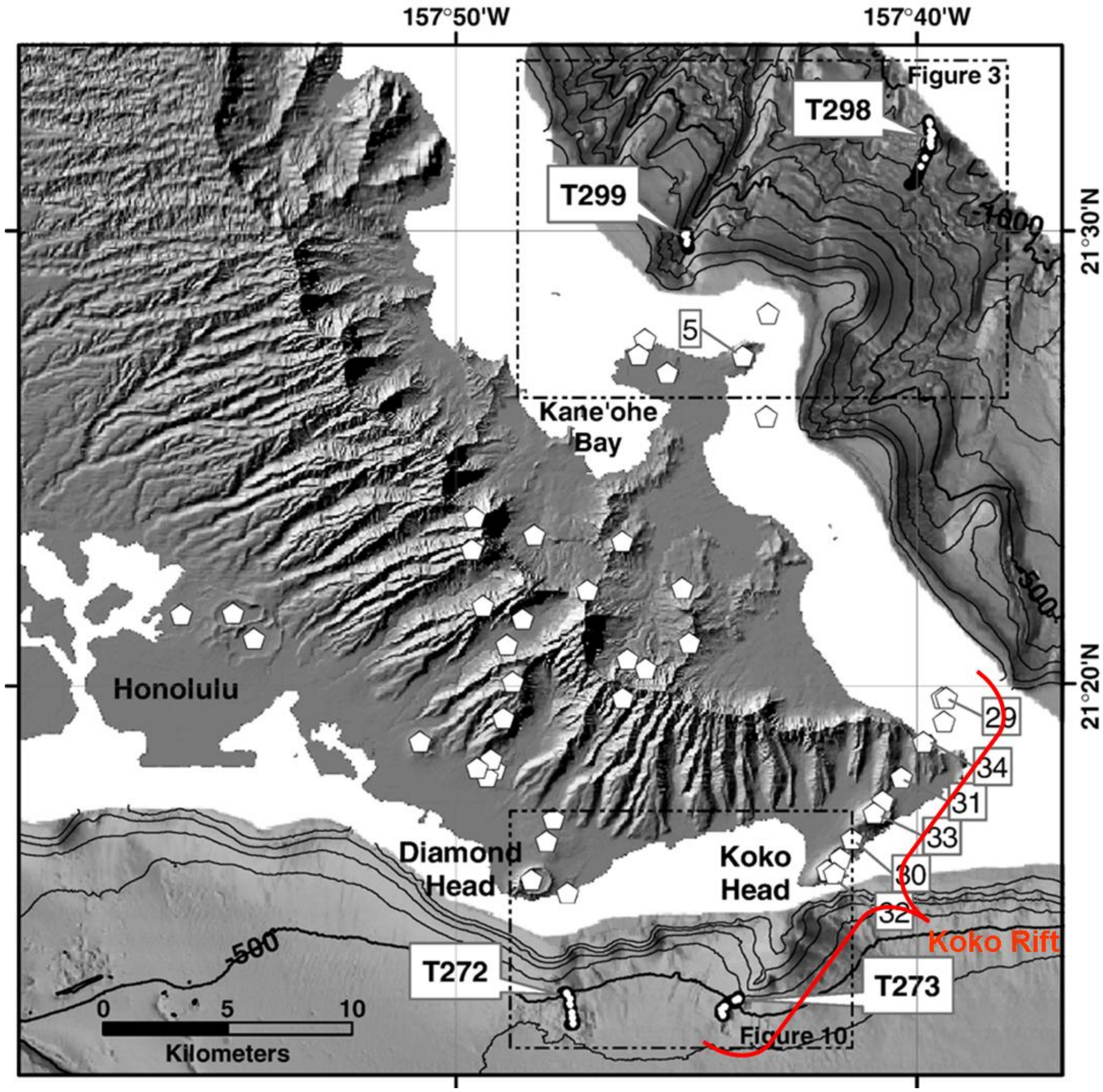

Figure 2. Map of eastern O‘ahu with topography displayed as a sun-illuminated image from the northwest and offshore shown as a slope-illuminated image with 100 m contours. The 37 known subaerial vents or groups of vents comprising the Honolulu Volcanics are indicated by pentagons (after Clague et al. 2005). Koko Crater is the vent labeled “33.”

2.0 KOKO CRATER STUDY AREA

The study area is located along the southeastern (seaward) base of Koko Crater where roadcuts, sea cliffs and other exposure on the lower flanks of the cone are easily accessible.

2.1 LOCATION OF STUDY AREA

Four sections were logged in detail selected (Fig. 3). One is located at the contact with overlying Hanauma Bay tephra, one is on shallow dipping flanking apron of Koko Crater, and two are on lower steep outer slopes of Koko Crater. The logged area in contact with the Hanauma Bay tephra may actually be on an older rim or slide block.

Figure 3. Aerial photo of Koko Crater showing double crater and location of logged sections.

2.2 DESCRIPTION OF TEPHRA IN STUDY AREA

The study area included four detailed logs across the SE edge of Koko Crater (Figure 3). Log 1 was taken at a location near the eastern on a road-cut along the Kalanianaole Highway. Location 2 is approximately 512 m west of Location 1, location 3 is located below the highway and is approximately 220 m east of Location 1, and location 4 is also located below the highway approximately 145 m from Location 3. The logs are illustrated below in Figs. 5 to 15.

2.2.1 Log 1

The first detailed log was located at a road cut along the Kalanianaole Highway, on the southeastern edge of Koko Crater. Location 1 generally consists of slumped, massive tephra below bedded lapilli tephra. There is prominent sagging below bombs and the bombs seem to be influencing the deposition of the sediment above them, in the sense of development of coarser lenses on one side of them. This suggests lateral emplacement (i.e. flow) of at least some of the bedded tephra. The uppermost unit of this log is interpreted as being derived from the Hanauma Bay tuff rings, due to the fact that it contains a few % of coral clasts that are rarely seen in the Koko Crater deposits, but are common in the Hanauma Bay tephra. The dip of the beds exposed in this road-cut varies from almost horizontal to roughly 15 degrees to the south. Unit 1 clearly pinches out to the west and Unit 4 to the east.

Unit 1 is massive and contains rounded, fairly well sorted glassy sideromelane lapilli of less than a few centimeters with a few % ashy matrix and some lithic crystalline basaltic lapilli. Pieces of lapilli sized reddened basalt lava flow tops are also present, but form less than 1 vol. %. This lapilli has a sharp upper contact with Unit 2 in most locations, with some local scours cut into its upper surface. Hardly any lithic blocks (1-2%) are present within this unit. Unit 1 thickens to several meters to the west of the log; elsewhere along this roadcut it is absent.

Unit 2 displays 4-6cm parallel bedding persistent over a few meters with some lenses being 10s of cm. The lapilli are slightly smaller in diameter than Unit 1 but are well sorted with rounded clasts and very few coral lapilli clasts (<1%). Within 40 cm from the top of Unit 2, the lapilli transitions into finer clasts and is laterally continuous to 10s of meters. Bomb sags become prominent at this fining upward transition, however there are lenses of large blocks throughout the unit. It should be noted that Units 2 & 3 have alternating ash rich/lapilli rich layers.

The basal transition between Unit 2 and Unit 3 protrudes as a more resistant boundary layer. Prominent bombs, which have dropped into an ashy, laminated layer comprise the base of unit 3. Unit 3 is similar in grain size, shape and composition to Unit 2, but has a greater abundance of bombs. The top of Unit 3 contains a very small amount of coral (1-2%).

Throughout this log, the bombs vary in vesicularity. The more vesicular juvenile bombs are assumed to be from new magma originating from the same Koko vent as the juvenile lapilli. Variably to less vesicular bombs are interpreted as being derived from the pile of Koolau basalt the Koko basalt erupted through. Koolau bombs/blocks tend to be angular and often more altered.

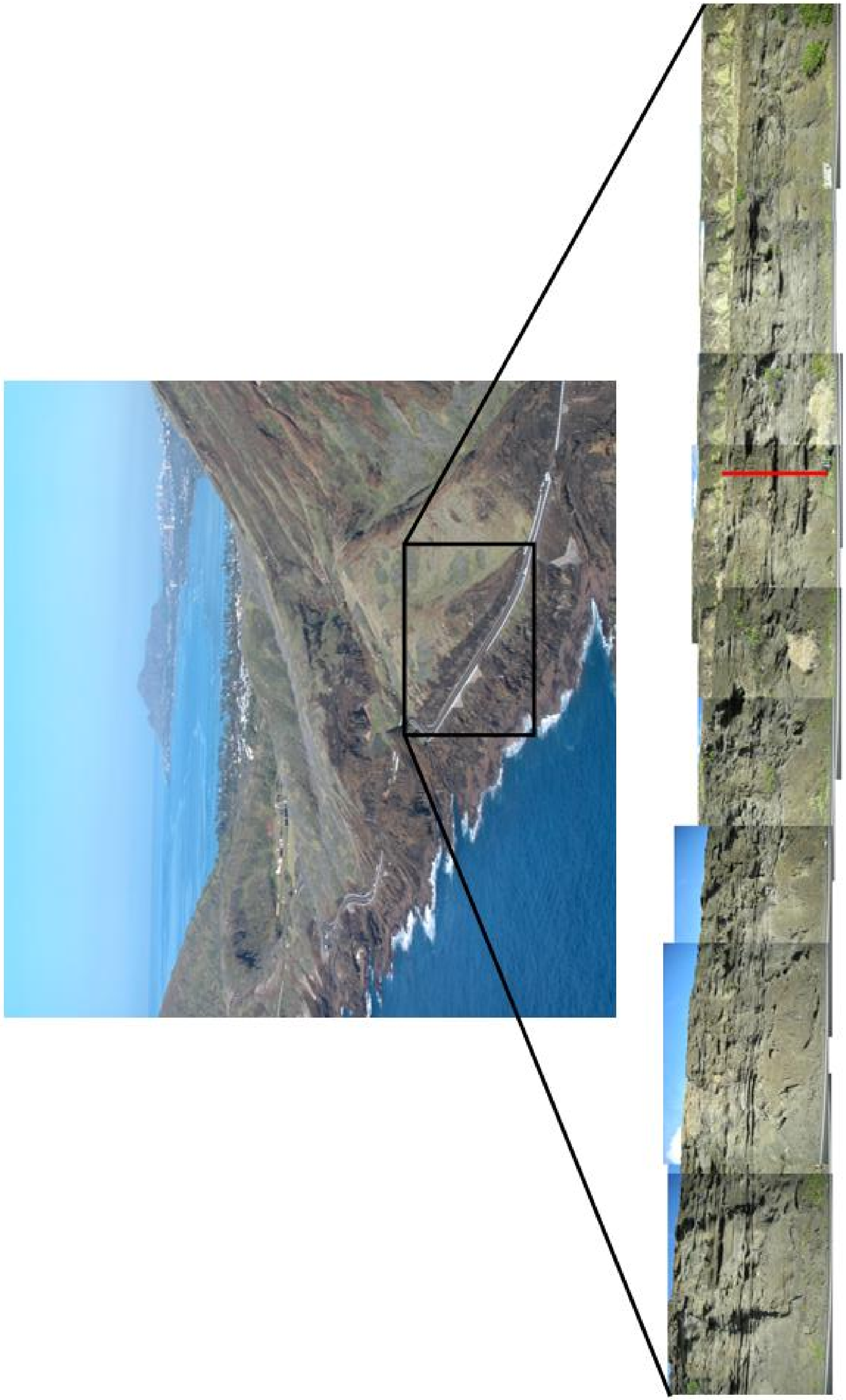

Figure 4. Panoramic of logged section 1 with stratigraphic column in red.

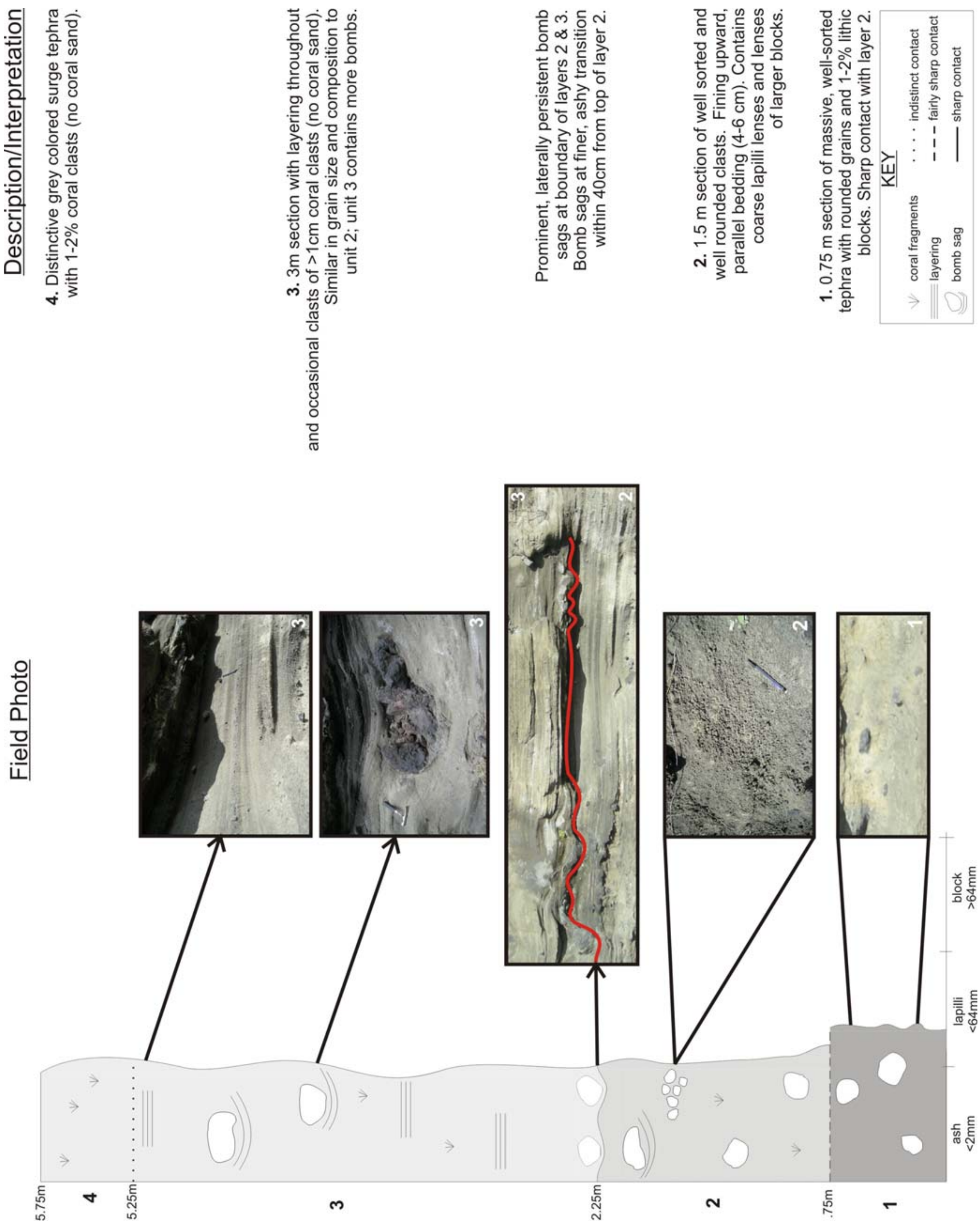

Figure 5. Log of location 1.

Figure 6. Log 1, location 1.

2.2.2 Log 2

Log 2 deposits were studied at a roadcut approximately 512 m to the west of Location 1 along the Kalanianaole Highway. The deposits seem to be slumping into an old channel or gully, striking 30NE and dipping to the SW (Fig. 9)

Within Log 2, Unit 1 is very similar to Units 2 and 3. The deposits here are all massive, with rounded, well-sorted lapilli (~2cm), but also display areas of convoluted bedding. Some indistinct centimeter scale layering is locally present along. Juvenile and non-juvenile bombs occur in local clusters. Intraclasts of older, consolidated tephra are present in the gully floor.

Unit 2 consists of a darker colored tephra and appears to be better bedded than Unit 1 with 1-4 cm beds, dipping N40E, 20SE, of alternating coarser and finer lapilli sizes. Unit 3 has a higher ash content and consists of fine-grained tephra with a maximum bed thickness of ~40cm, averaging at around 15cm. Unit 3 also contains some distinct lenses of armoured lapilli, and possible polygonal dehydration cracking. This unit also contains hints of polygonal cracking. Unit 4 is identical to Unit 2 in this log.

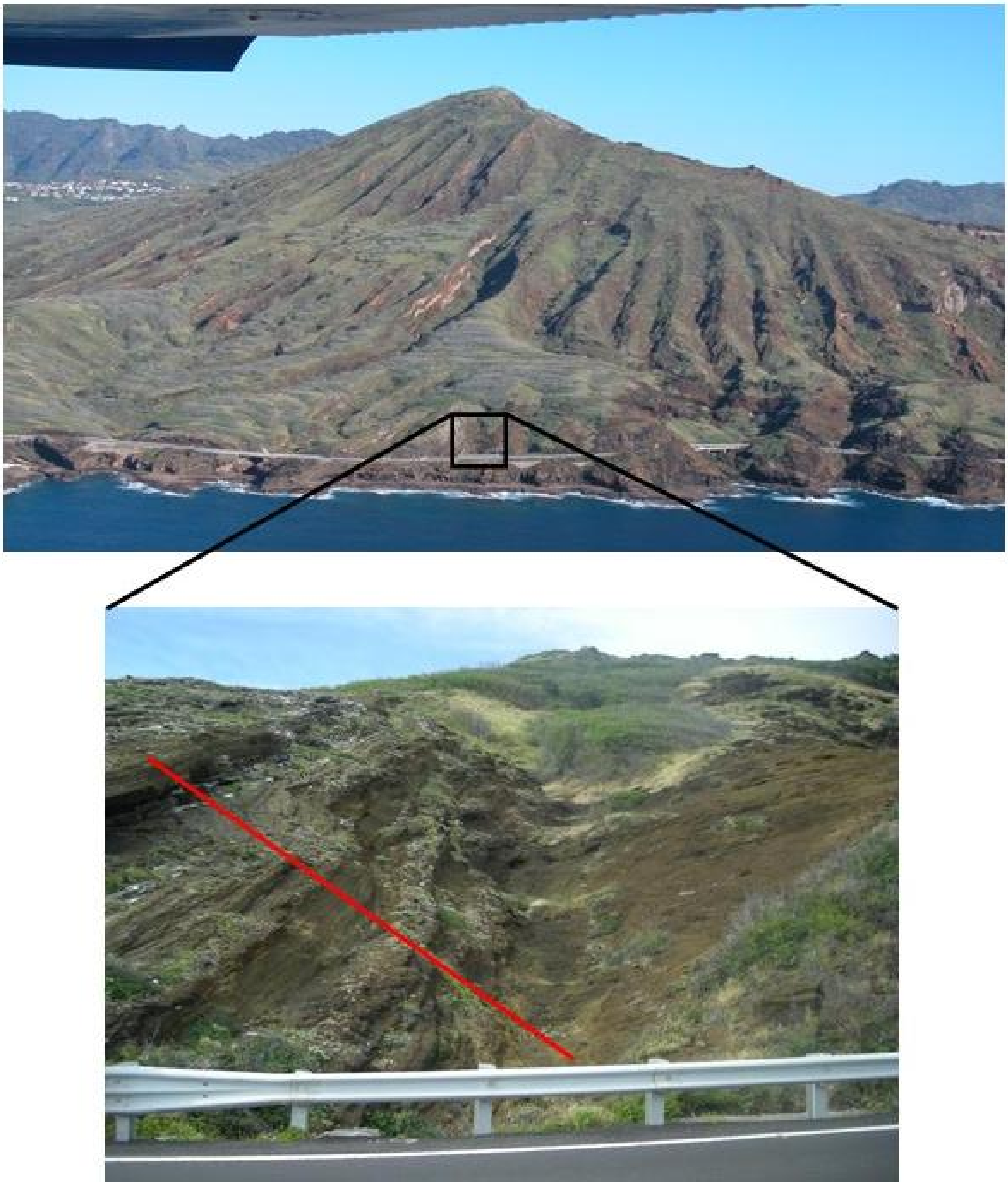

Figure 7. Logged section (in red) at Location 2.

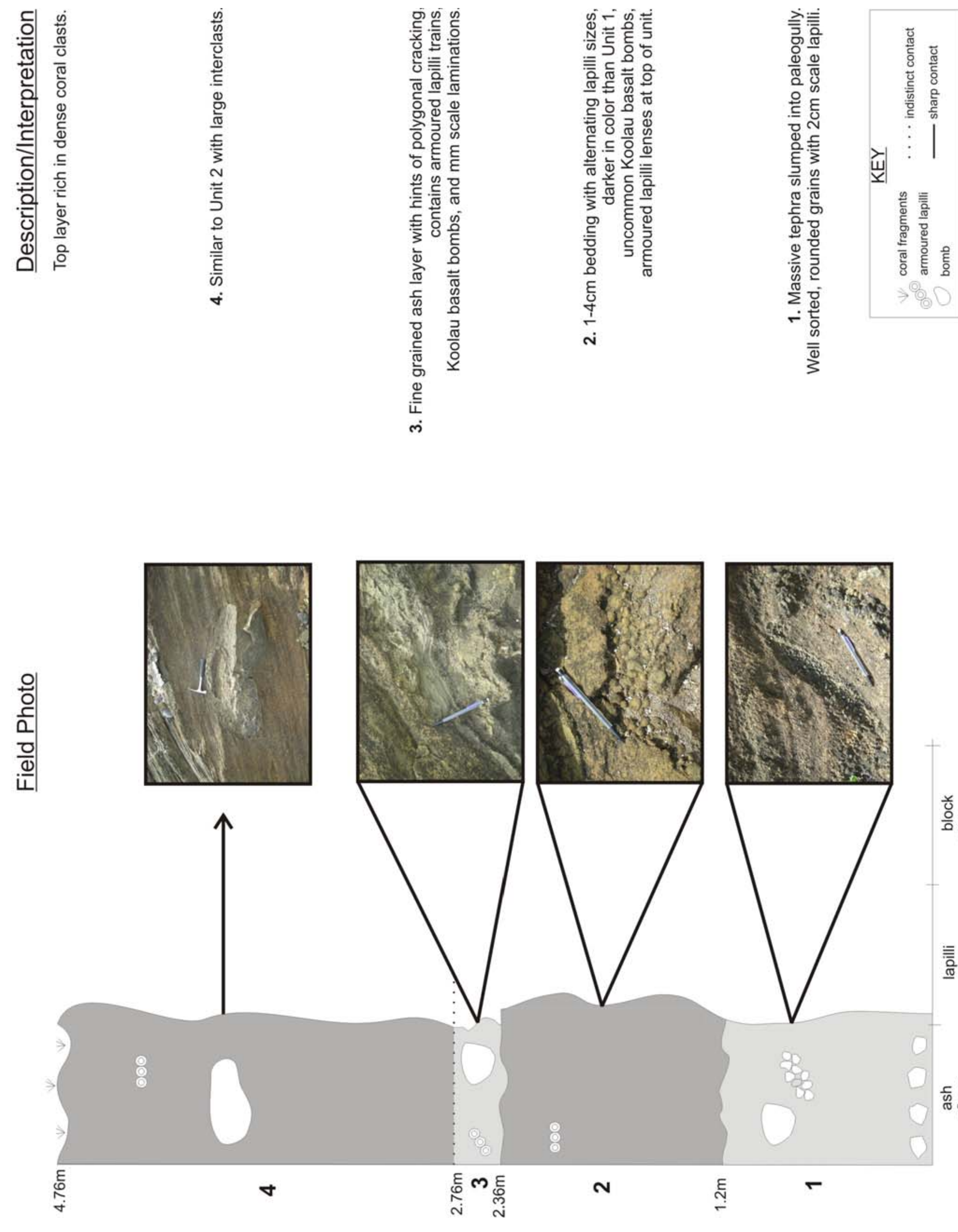

Figure 8. Log of location 2.

2.2.3 Log 3

The deposits in this location (Figs 11-13) are much better bedded than at Location 1 and 2, and are not as highly palagonitized, with more angular clasts. The dips of the beds are almost horizontal to the SW and there is a lack of syn-eruptive drainage channels within the deposit. Coarser lapilli are more black and appears “more fresh,” whereas the matrix looks just as palagonitized, with a more prominent yellowish-orange hue. There are some coral clasts that appear to be in lenses toward the base of the unit, but no coral sand in the matrix. Coarser lenses toward the bottom of the unit incorporate a more heterolithic group of clasts. Within these lenses, the clasts are well sorted. When these lenses are observed in plan view, they are approximately 1 m wide and irregular in shape (Fig. 12). Some larger clast lenses, only about 1%, reach lengths of 10-20 cm. This location also contains some syn-sedimentary folds and faulting (Fig. 13). Fault breccia with hydrothermal mineralization is present to the east of the section.

Figure 9. Logged section of location 3.

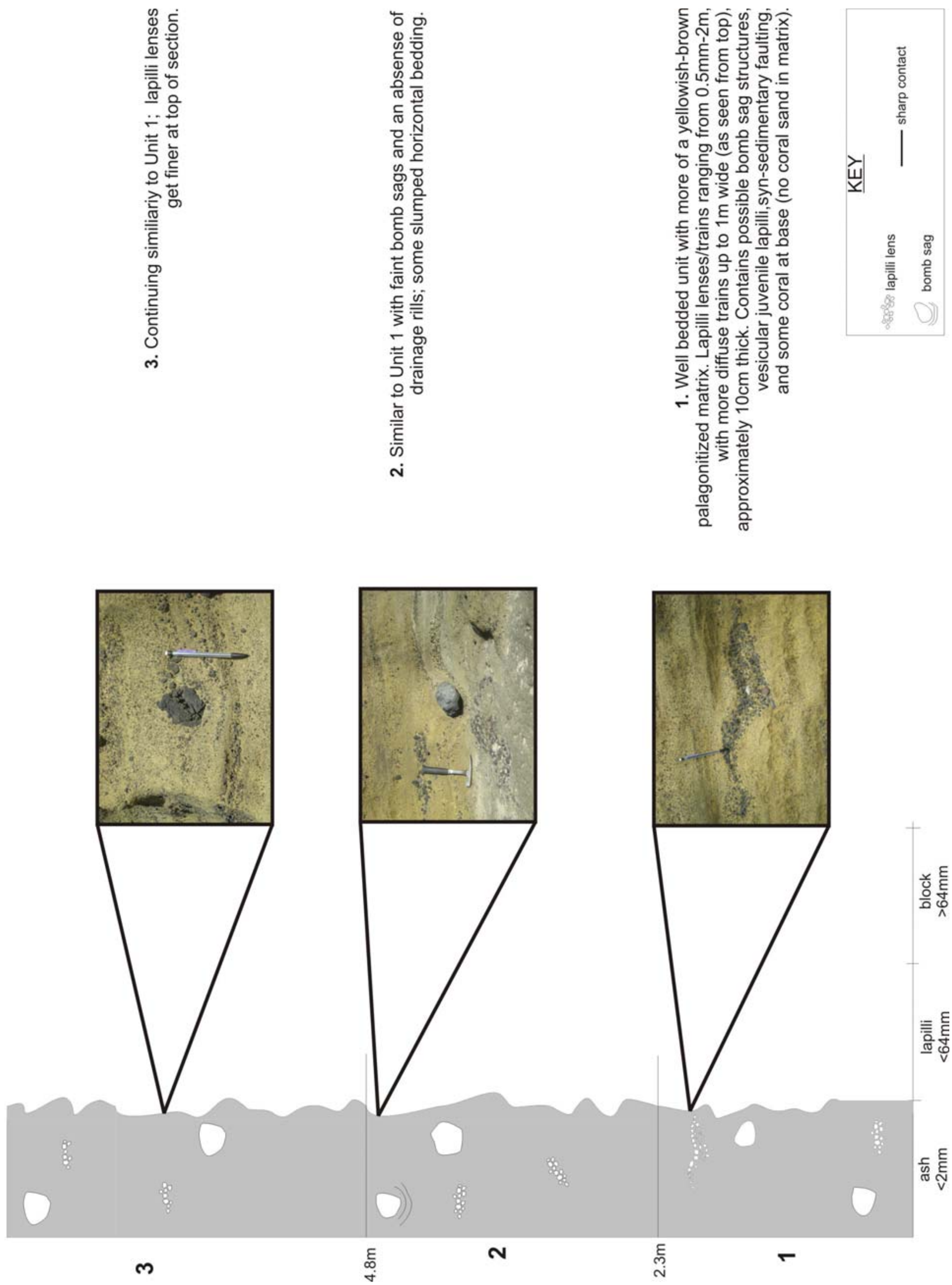

Figure 10. Log of location 3.

Figure 11. Coarse lapilli lenses (viewed from above).

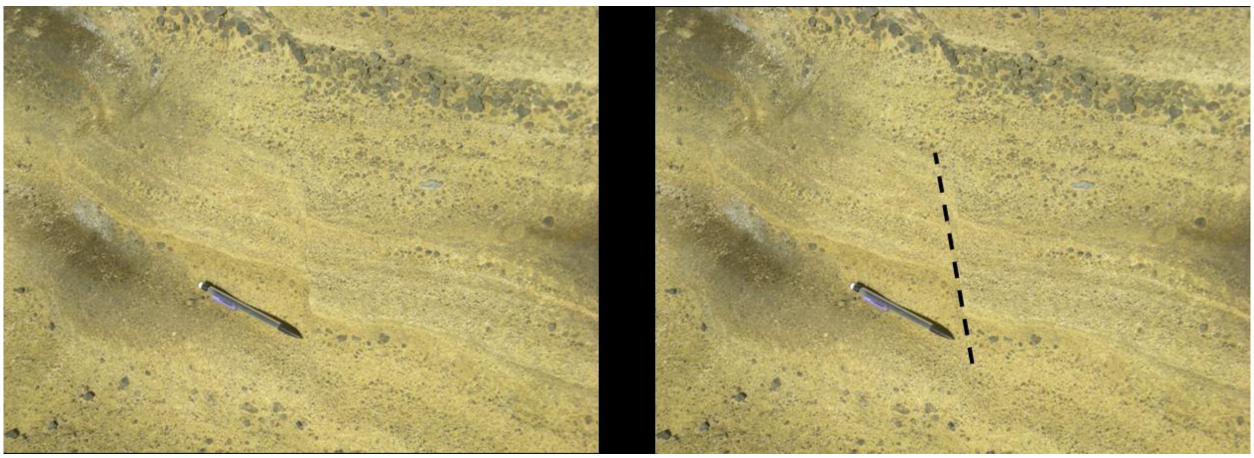

Figure 12. Syn-sedimentary faulting.

2.2.4 Log 4

Unit 1 is very similar in appearance to Location 3, but contains a higher abundance of bombs, most appearing juvenile in origin. Lenses of black lapilli are less prominent and syn-sedimentary folding and faulting is less obvious at this location. This unit also contains more coral clasts than other units in this log.

Unit 2 consists of a fine ash with varying bedding thickness (to a meter thick) and mm to cm scale lamination. Cross lamination and truncation surfaces are present and there are significant bomb sags but an absence of lapilli trains and rills. This section thickens to a coarser, more ash-rich package north of the section with a variance of the dominant grain size.

Unit 3 is laminated at the cm scale of ashy layers within the basal 10cm. The unit is similar to Unit 1 but contains a large number of Koolau basalt blocks, and juvenile lapilli trains along with <1 vol% of coral lapilli.

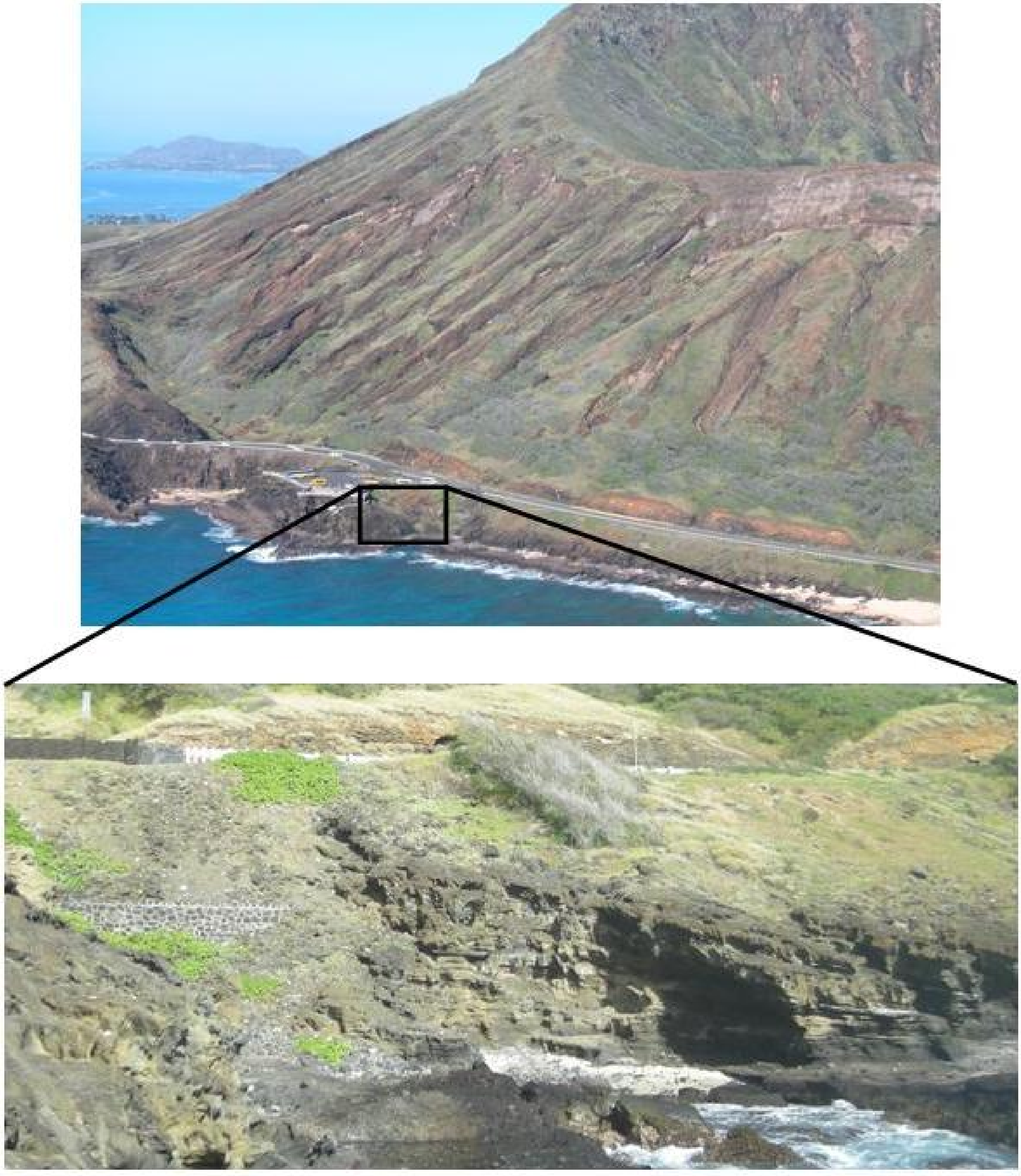

Figure 13. Logged section at location 4.

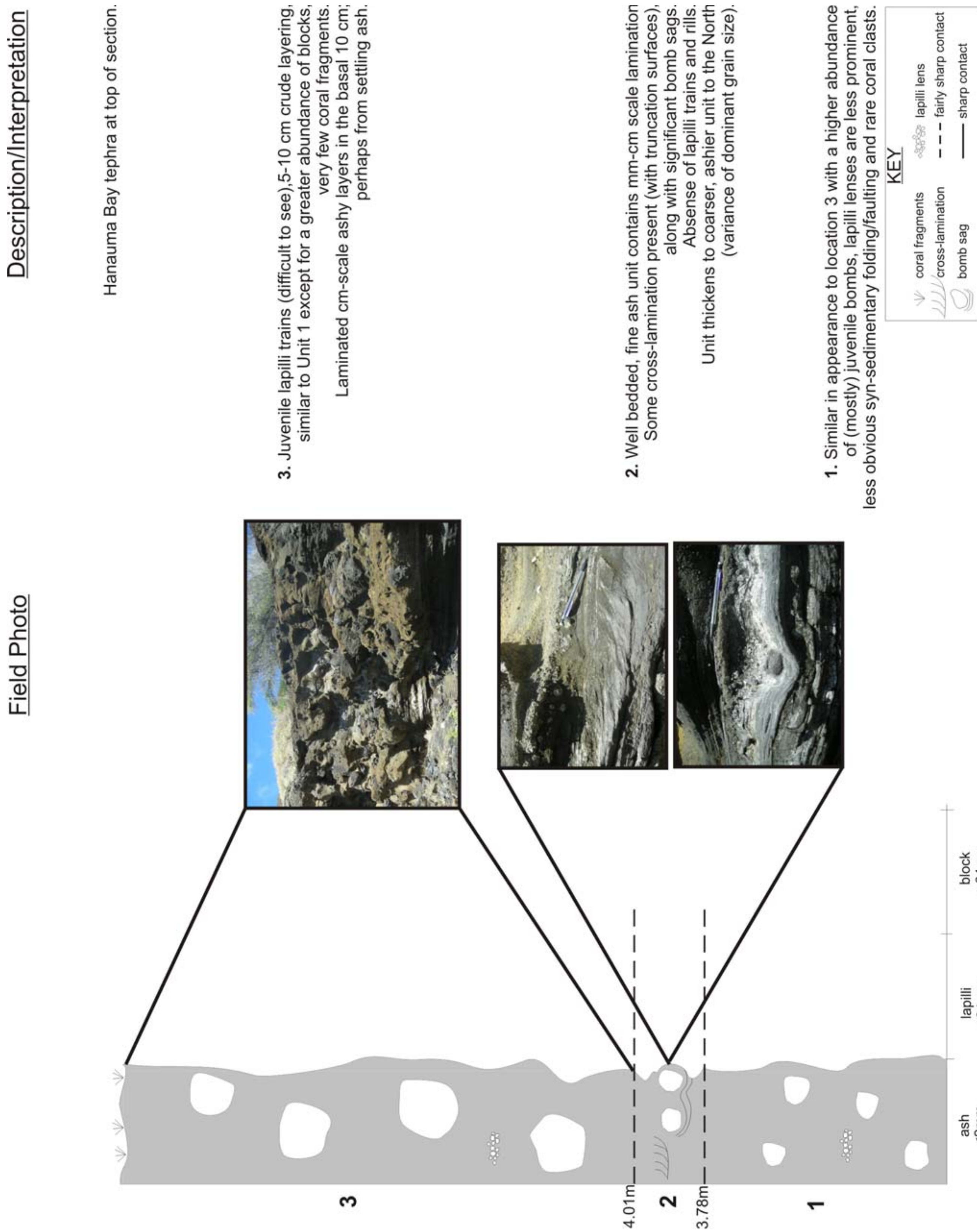

Figure 14. Log of location 4.

3.0 ERUPTION AND EMPLACEMENT OF PHREATOMAGMATIC TEPHRA

3.1 CONTROLS ON TUFF CONES VS TUFF RINGS

Tuff cones and tuff rings are the most common hydrovolcanic landforms on Earth. These are monogenetic volcanoes as they are largely constructed by a single eruptive event, which can persist for several years. Tuff cones and tuff rings are also the second most common type of volcanic edifice of any type.

Tuff rings exhibit low topographic profiles, with thin (less than 50 m) sections of rim beds and gentle slopes that are characteristically less than 15°. Central craters are wide and where they are depressed below the pre-eruptive ground surface, the edifice is classified as a maar. Tuff cones have similarly wide central craters, but display steep outer slopes (greater than 25°) and sequences of rim deposits that exceed 100 m in thickness (Wohletz and Sheridan, 1983).

Basal deposits of both tuff rings and tuff cones are commonly explosion breccias (or finer deposits) composed of angular fragments of country rock supported in an ash/lapilli matrix. Breccias represent pre-existing surficial material at the vent that is shattered during the initial explosions (Wohletz and Sheridan, 1983). In tuff rings, the overlying apron of tephra is fine-grained and thinly bedded. Traction current, massive, and planar bedforms indicate that emplacement is dominantly by highly inflated pyroclastic density currents. Tuff cones largely comprise thick units of weakly bedded or massive tephra largely deposited from steam-laden (wet) pyroclastic density currents and fallout (White, 1991). Lapilli- and/or ash-fall beds are more abundant than in tuff rings. Additionally, tephra are relatively coarser and commonly hydrothermally altered to palagonite (Wholetz and Sheridan, 1983; Heiken and Wohletz, 1985).

The morphological and compositional differences between tuff rings and tuff cones are attributed to a wide variety of factors. Fundamental among these factors is variation in the energy of eruption, which in turn affects both the eruption temperature and subsequent depositional processes. Eruption temperature determines the state of erupted water (and, consequently, the pyroclast transport medium) and grain sizes of ejected tephra as the degree of fragmentation is largely determined by the efficient conversion of thermal to mechanical energy. Depositional processes, namely pyroclastic density currents and fallout, are influenced by several features in addition to eruption energy, including depositional setting (shallow submarine, lacustrine, etc.), competence of country rocks, level and lithology of aquifers, and properties and behavior of magma (Sohn, 1996). These factors subsequently influence explosion depth, conduit geometry, mode of magma-water interaction, and magnitude of explosion (Sohn, 1996).

Tuff cones typically include more intensely palagonitized tephra than tuff rings. These characteristics indicate cool (below 100°C), wet emplacement where the majority of erupted water was condensed (or condensing). Combined with coarser grain sizes, which reflect less intense fragmentation, it is apparent that less energetic eruptions are involved in the construction of tuff cones as compared to tuff rings.

3.2 ERUPTION MECHANISMS AT MAFIC TUFF CONES

A phreatomagmatic eruption is driven primarily by the volumetric expansion of external water after it has been rapidly heated by contact with magma, with exsolving magmatic volatiles often contributing to expansion and fragmentation during the eruption. When water comes into contact with magma, it will either transform to vapor or a two-phase liquid-vapor fluid, or become superheated to a metastable liquid state which will flash to steam when acted on by an external source. Theoretically, phreatomagmatic eruptions result from the interaction of magma and water at any location in the conduit. In the specific case where external water accesses the top of the vent, either by direct flooding or seeping through walls of an accumulating tephra ring, Surtseyan-type eruptions commonly result (Kokelaar, 1983). The 'Surtseyan' style was aptly named for the well documented early eruptive stages of Surtsey Volcano, Vestmann Islands, Iceland in November 1963 (Fig. 16). Surtseyan eruptions are characterized by cypressoidal explosive jets of ash accompanied by billowing clouds of steam, but also commonly alternate with more sustained eruption columns, often called "continuous uprush". Ejecta are directed vertically and laterally with the laterally directed ejecta producing a base surge or "wet", low concentration pyroclastic density currents.

Figure 15. Eruptive phase of Surtsey Volcano, Iceland in 1963. A convective vertical eruption column (left) and tephra-finger jets (right) illustrate intense explosive activity. Relatively tephra-free columns of steam rise (and collapse) at the margins. Jets illustrate density separation of tephra and condensed steam (from Thorarinsson, 1964).

Surtseyan eruptions comprise three types of activity: pulsating explosions of "tephra-finger" or "cock's tail" jets, phases of continuous uprush wherein large sustained (up to 10 km) vertical eruption columns are produced, and (commonly) magmatic activity that produces lava flows and scoria, whenever water is denied access to the vent (Thorarinsson et al., 1964). The eruptions typically begin with the intermittent, explosive, ballistic ejection of black jets of tephra. These explosions propel bombs and finer tephra several hundred meters into the air, and can be separated by several seconds, with smaller explosions occurring in between (Thorarinsson et al., 1964). The frequency of jetting reflects the rate of supply of magma into the vent and/or the time for sufficient heat transfer to the water to occur. When discrete explosions occur so frequently that individual events can no longer be distinguished, phases of continuous uprush activity ensue. Continuous uprush is characterized by the production of columns of tephra and steam that can reach altitudes of several kilometers and persist for several hours. Base surges, which are "wet," below 100°C, low-concentration pyroclastic density currents, are also common occurrences during such phases of Surtseyan eruptions. These largely result from (1) the inclined ejection of steam and tephra and (2) partial column collapse, particularly at the margins where air resistance is greatest (Waters and Fisher, 1971).

Numerous magma-water mixing models are described in literature, however, recent work points to just two theories that satisfactorily explain most explosions that occur during the contact of a hot fluid with a cold one, i.e. a fuel coolant interaction or FCI. The analogy of hydrovolcanic activity to FCIs appears to be a useful approach to understanding eruption dynamics. Specifically, the liquid instability and thermal detonation analyses satisfactorily explain how magma and water can sufficiently intermingle to produce large explosions FCI is such a general physical process that it includes phenomena ranging from passive quenching, permitted by insulating steam envelopes, to dynamic explosions resulting from instability of film boiling interfaces (Wohletz, 1986). The spontaneous nucleation (superheating) model and the thermal detonation model are the two theories for explosive behavior. Both models require that a period of film boiling should occur prior to explosion, which permits two processes to occur simultaneously, namely partial thermal insulation of the molten magma from the water, and gradual fragmentation and mixing of the magma with water by the instabilities arising from film boiling. The following controls complicate the physical analysis of explosive, magma-water interaction: (1) initial geometry and location of the contact between the magma and water; (2) the process by which thermal energy is transferred from the magma to the water; (3) the degree to and manner by which the magma and water become intermingled prior to eruption; (4) the thermodynamic equation of state for mixtures of magma fragments and water; (5) the dynamic metastability of superheated water; and (6) the propagation of shock waves through the system (Wohletz, 1986).

4.0 INTERPRETATION AND DISCUSSION

Logged sections of the tephra at the SE corner of Koko Crater are representative of the bulk of the tephra emplaced from this tuff cone and illustrate that typical wet steep slope redepositional (syn or post-eruptive) mechanisms, such as slumps, slides and cohesionless debris flows were important emplacement processes. Most of the logged massive deposits are interpreted as either debris flow deposits, slumps or in rare cases, might be primary wet fallout deposits. Stratified deposits are probably mostly primary fallout or in some cases may represent deposits of dilute PDCs. Rare large (>1cm coral fragments and Koolau Basalt ("country rock") fragments) are interpreted as vent-wall derived lithics. Syn-depositional rilling, polygonal cracking, bomb sags and slumps are all indicative of very wet deposits, which combined with the typical "Surtseyan" emplacement mechanisms may indicate open-water flooding of the vent. This is in contrast to the younger tephra from the Hanauma Bay tuff rings, which are dominated by well-bedded well-sorted finer tephra with abundant traction current structures, interpreted as PDC deposits. This tephra is not described here (Skilling, unpublished) but includes abundant coral sand, implying that while Koko was erupted in open water, the later Hanauma craters were erupted through what was probably beach sand, close to or at the shoreline.

The tephra at logs 1 and 2 is interpreted as dominantly massive and convolute-bedded, erosive-based, slumped fallout tephra on the steep outer flanks of Koko Crater, overlain by in-situ pyroclastic fallout and possible thinner-bedded cogenetic PDC deposits. It is possible that this upper bedded (or better-bedded) tephra did not slump do to a shallowing of the outer slope topography following the slumping of the underlying tephra. Lee-side lenses of coarser lapilli behind bomb sags may indicate primary PDC emplacement, but could also be due to downslope massflow of fallout deposits, including of course, during slumping.

The much better developed mm- and cm-scale bedding, lensoid areas of well-sorted lapilli, and much less common bomb sags, of the tephra at logs 3 and 4 are interpreted as evidence of dominantly primary PDC deposition, with minor cogenetic fallout. Logs 3 and 4 located on the shallower sloped flanking apron of the cone, where the dominance of PDC deposits may be due to longer transport distances than the ballistic fallout dominated areas of logs 1 and 2. The local presence of convolute folds and syn-sedimentary faulting at log 3, illustrate that the flanking apron deposits were subject to downslope movement post-deposition, but this is minor compared to the major slumping on the steep outer flanks of the cone.

BIBLIOGRAPHY

Clague, D.A., Paduan, J.B., McIntosh, W.C., Cousens, B.L., Davis, A.S., and Reynolds, J.R., 2005, A submarine perspective of the Honolulu Volcanics, Oahu. *J. Volcanol. Geotherm. Res.*, 151: 279-307.

Easton, W.H. and Olson, E.A., 1976, Radiocarbon profile of Hanauma Reef, Oahu, Hawaii. *Geol. Soc. Am. Bull*., **87**: 711-719.

Gramlich, J.W., Lewis, V.A. and Naughton, J.J., 1971, Potassium-argon dating of Holocene basalts of the Honolulu volcanic series, *Geol. Soc. Am. Bull*., **82**: 1399-1404.

Hay, R.L. and Iijima, A., 1968, Petrology of palagonite tuffs of Koko Craters, Oahu, Hawaii, *Contr. Mineralogy and Petrology*, **17**: 141-154.

Heiken, G. and Wohletz, K., 1985, Volcanic Ash. University of California Press, Berkeley, 246 pp.

Kokelaar, P., 1983, The submarine eruption and erosion of Surtla (Surtsey), Iceland. *J. Volcanol. Geotherm. Res.*, **19**: 239-246.

Macdonald, G.A. and Abbott, A.T., 1970, Volcanoes in the sea: The geology of Hawaii, University of Hawaii Press, Honolulu, 441 pp.

McPhie, J., Doyle, M. and Allen, R., 1993, Volcanic Textures: a guide to the interpretation of textures in volcanic rocks, CODES University of Tasmania, Australia, 198 pp.

Self, S. and Moberly, R., 1997, Phreatomagmatic volcanism and geology of southeast Oahu, *Cordilleran Section Meeting of the Geological Society of America, Kailula-Kona, May 21-23*, 1997: 1-34.

Sigurdsson, H., Houghton, B.F., McNutt, S.R., Rymer, H. and Stix, J. (eds) Encyclopedia of Volcanoes, Academic Press, San Diego, USA: 683.

Sohn, Y.K., 1996, Hydrovolcanic processes on Cheju Island, Korea. GSA Bulletin, 108 (10): 1199-1211.

Stearns, H.T. and Vaksvik, K.N., 1935, Geology and groundwater resources of the island of Oahu, Hawaii. *Bull. Hawaii Div. Hydrography*, **1**: 1-479.

Thorarinsson, S., 1964, Surtsey, the new island in the North Atlantic, Viking Press, New York, 47 pp.

Thorarinsson, S., Einarsson, Th., Sigvaldason, G., and Elisson, G., 1964, The submarine eruption off the Vestmann Islands 1963-64: A preliminary report, *Bull. Volcanol.*, **27**: 435-445.

Waters, A.C. and Fisher, R.V., 1971, Base surges and their deposits: Capelinhos and Taal Volcanoes, *J. Geophys. Res.*, **76**: 5596-5614.

White, J.D.L., 1991, The depositional record of small monogenetic volcanoes within terrestrial basins. In: Fisher, R.V. and Smith, G.A. (eds) Sedimentation in volcanic settings, Soc. Sed. Geol. (SEPM) Special Publication 45: 155-171.

Winchell, H., 1947, Honolulu Series, Oahu, Hawaii, *Geol. Soc. Am. Bull.*, **58**: 1-48.

Wohletz, K.H. and Sheridan, M.F., 1983, Hydrovolcanic explosions II: evolution of basaltic tuff rings and tuff cones, *Am. J. Sci.*, **283**: 385-413.

Wohletz, K., 1986, Explosive magma-water interactions: Thermodynamics, explosion mechanisms, and field studies. *Bull. Volcanol.*, **48**: 245-264.